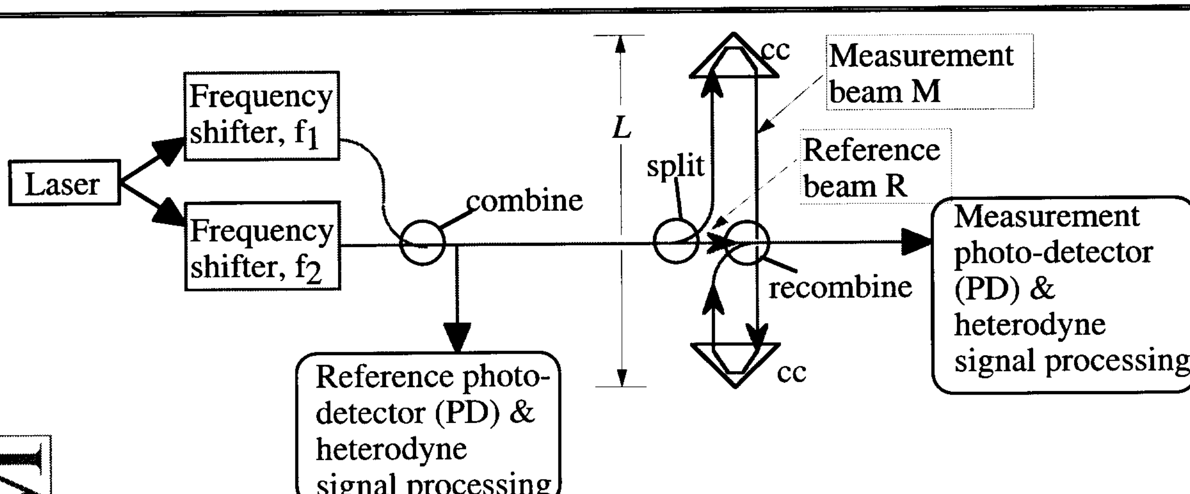
A SIM gauge:

SIM Space Interferometry Mission

- Must:
  1. Measure distance **between** two fiducials.
  2. Relative accuracy ~ 10 pm.
  3. Minimal sensitivity to metrology head mis-orientation.
  4. Minimal sensitivity to electronic drift. (Favor use of heterodyne technique.
  5. Be consistent with ~20 other gauges. (Requires use of single laser wavelength standard.)
- Basic components include:
  1. **Laser**, stabilized, λ=1.3 micron (to not contaminate starlight in the visible)
  2. **Frequency shifters** to enable heterodyne detection
  3. **Fiber optics** for laser light distribution to ~20 metrology heads
  4. **Metrology heads** (includes photodiodes which produce heterodyne interference signals)
  5. Fiducial **retro-reflectors** (corner cubes).
  6. **Electronics to measure phase** of metrology heads' heterodyne outputs.

A generic gauge

SIM Space Interferometry Mission



- Photodetectors detect heterodyne interference signal, f_2-f_1 (~100 kHz)
- Relative phase of Reference vs. Measurement photodiode signals tells us the Optical Path Difference (OPD) of the M beam vs. the R beam: basis for gauge readout. L=OPD/2.
- For λ=1.3 microns, we need to measure phase difference to 1.5x10^{-5} cycles.
- Incomplete split of M and R beams causes cyclic error.

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SIM Space Interferometry Mission

How precision engineering will help find planets like Earth.

A presentation to the students of Nagaoka University

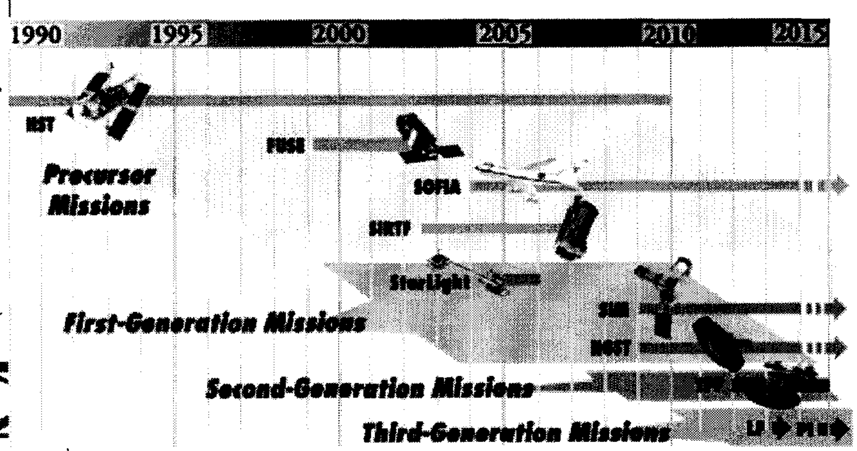
July 17, 2002

Peter Halverson

SIM Space Interferometry Mission

Planet finding missions: NASA timeline

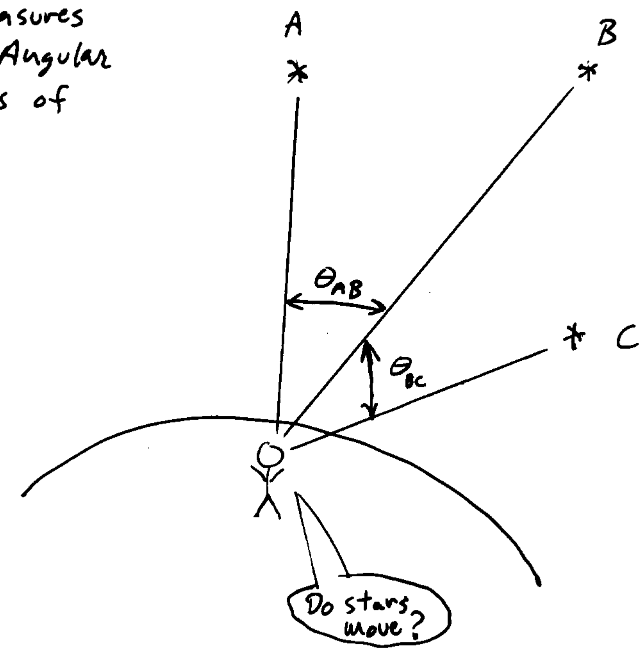
http://origins.jpl.nasa.gov/



- Hubble Space Telescope
- Far Ultraviolet Spectroscopic Explorer
- Stratospheric Observatory for Infrared Astronomy
- Space Infrared Telescope Facility
- Starlight
- **Space Interferometry Mission**
- **Next Generation Space Telescope**
- **Terrestrial Planet Finder**
- Life Finder, Planet Imager

SIM Space Interferometry Mission

SIM measures Relative Angular Positions of Stars



Yes, of course

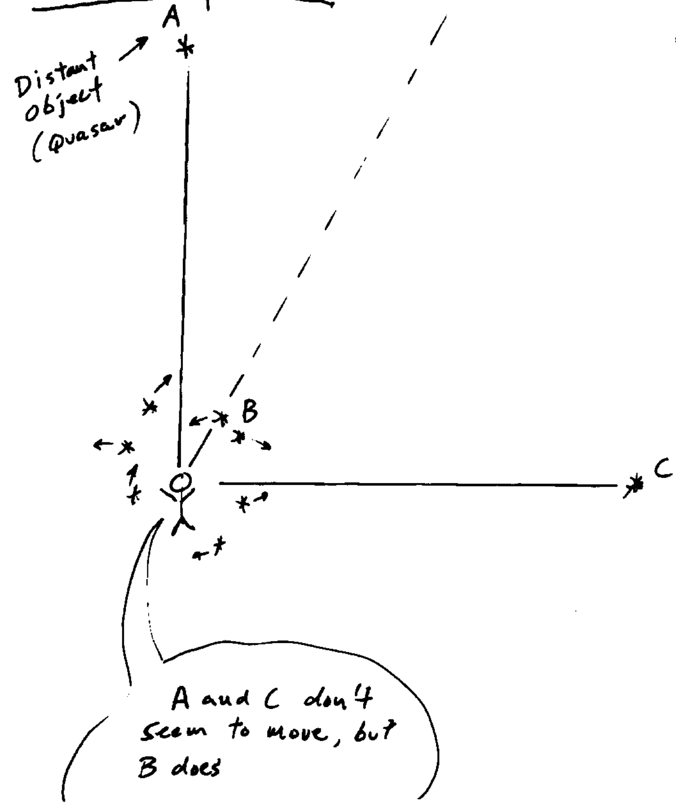
SIM Space Interferometry Mission

Stars appear to move because of

- Parallax
- Intrinsic proper motion (each star has its unique orbit about the center of the Galaxy)
- Gravitational pull of unseen partners orbiting (planets, brown dwarfs)

  NASA wants planets!
- Gravitational lensing
- Stellar aberration (relativistic effects)

Intrinsic Proper Motion



SIM Space Interferometry Mission

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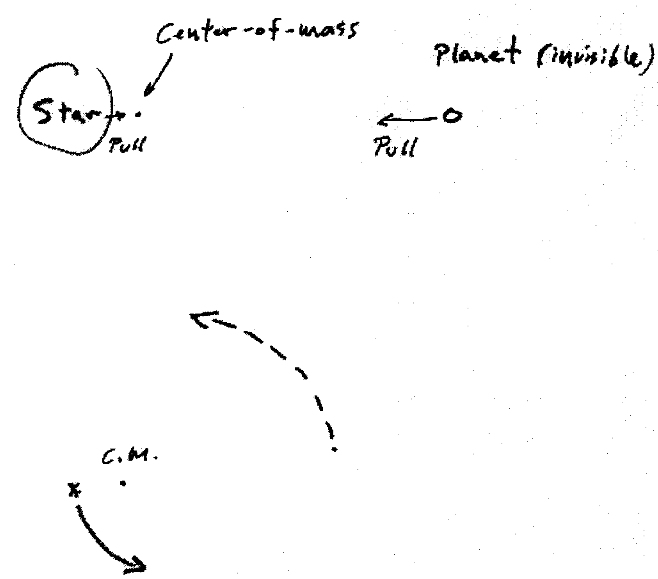
Gravitational Pull of Dark Partners



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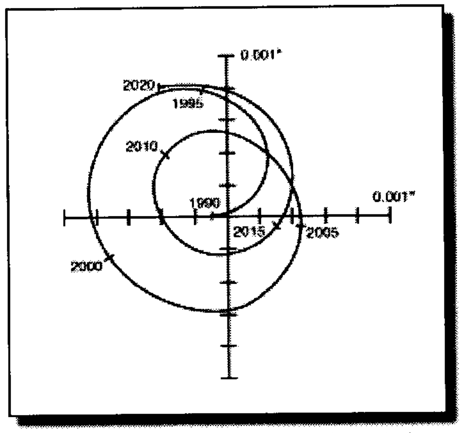
Planet detection with astrometry: reflex motion of stars due to gravitational pull of planets

SIM Space Interferometry Mission



Astrometric displacement of the Sun due to Jupiter as seen from 10 parsecs.

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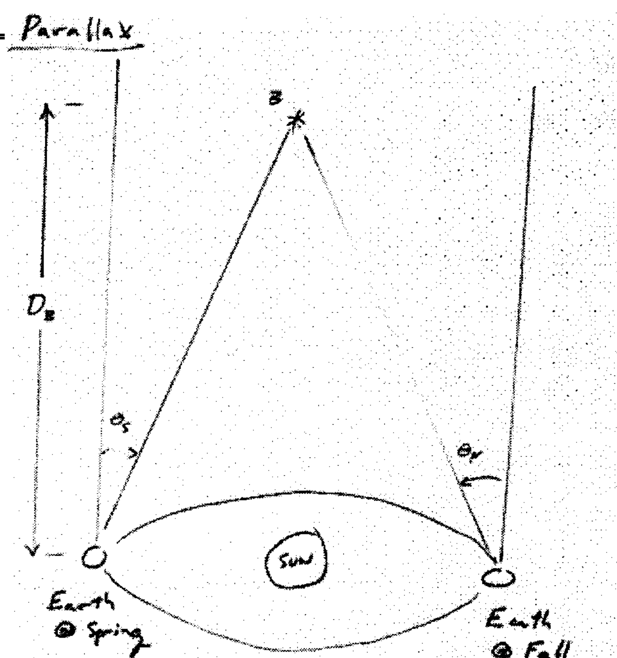

$\Delta\theta = \theta_f - \theta_s$

Use to calculate distance: $D_* = \frac{\Delta\theta}{\text{Earth-Sun distance}}$

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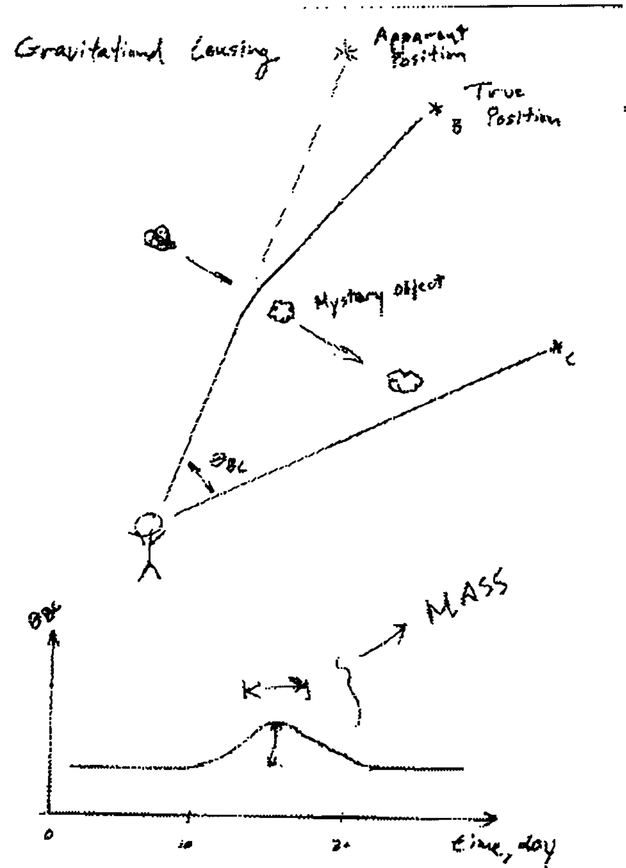

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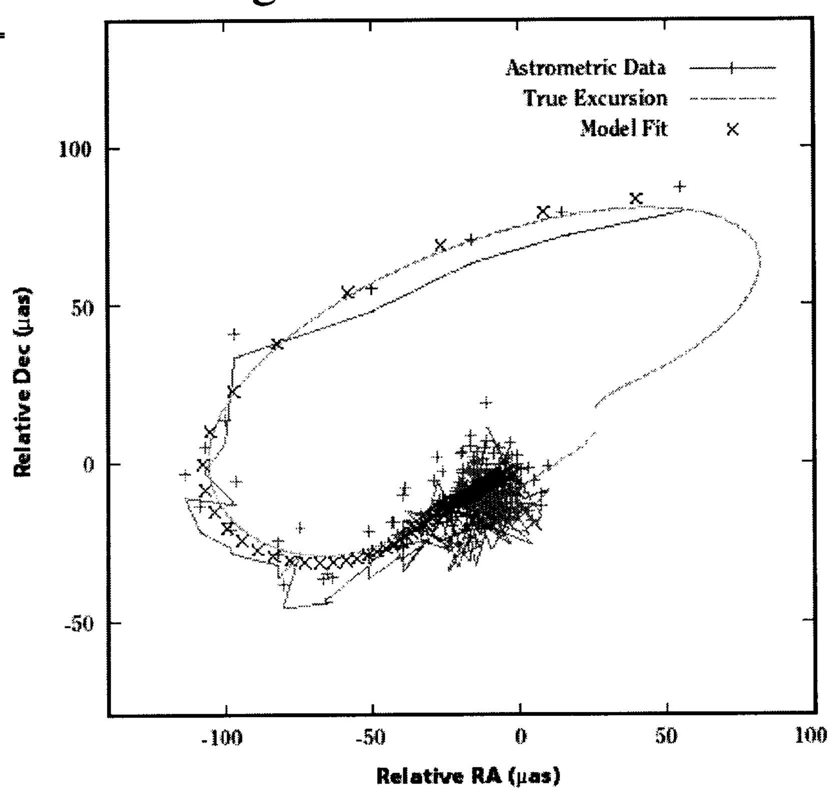
Gravitational lensing: simulated data

SIM Space Interferometry Mission

MICROLENSING IN THE LMC

Numerical simulation of the astrometric signature of a microlensing event in the Large Magellanic Cloud.



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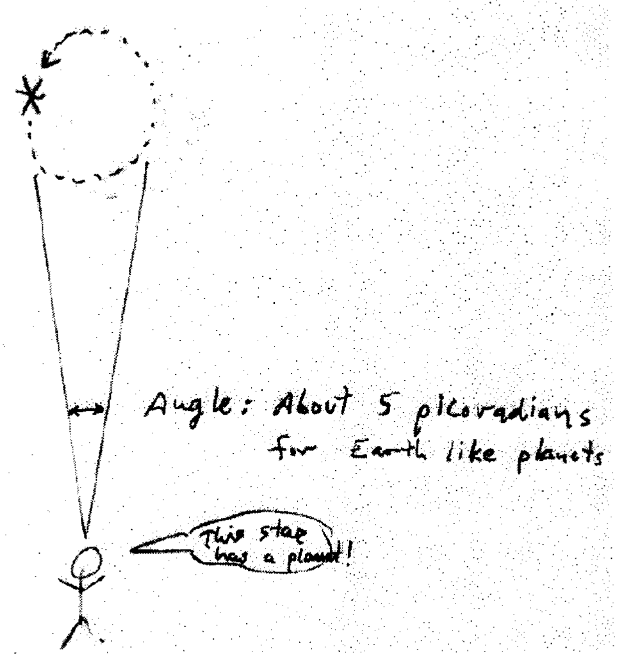
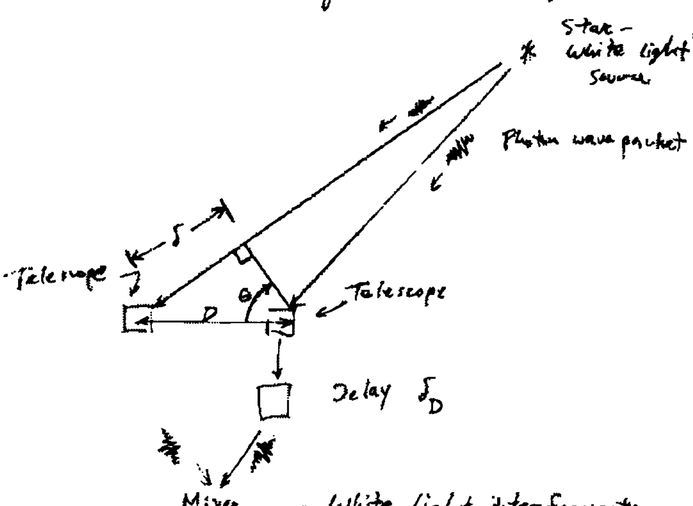
To find PLANETS...



SIM Space Interferometry Mission

Basic Idea - use pair of telescopes
to measure wavefront delay, the compute angle

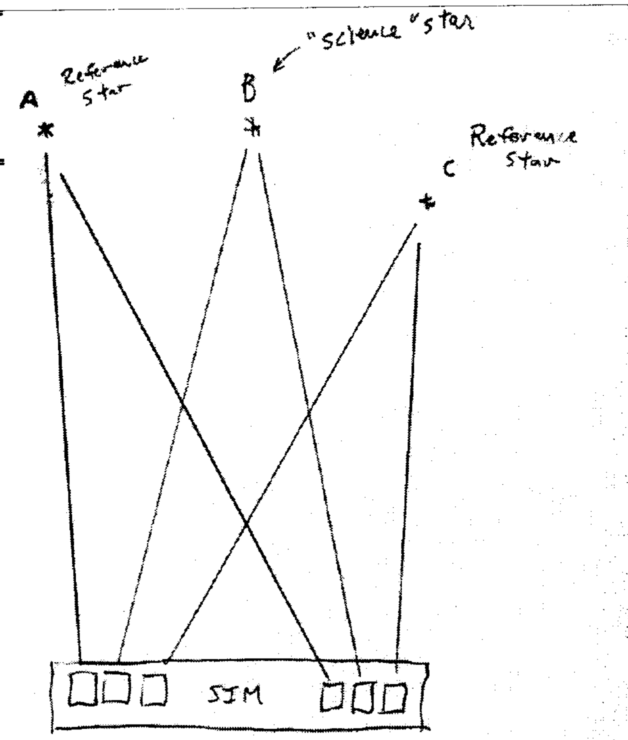


— White light interferometry
Only see fringes when
$\delta \approx \delta_D$
Maximise signal, get central
white light fringe, then $\delta = \delta_D$

Get results $\theta = \cos^{-1}\left(\frac{D}{\delta}\right)$

SIM Space Interferometry Mission

JPL



SIM has three ~~interferometry~~

A + C tell us SIM's angular position.

B tells us the science star's angular position.

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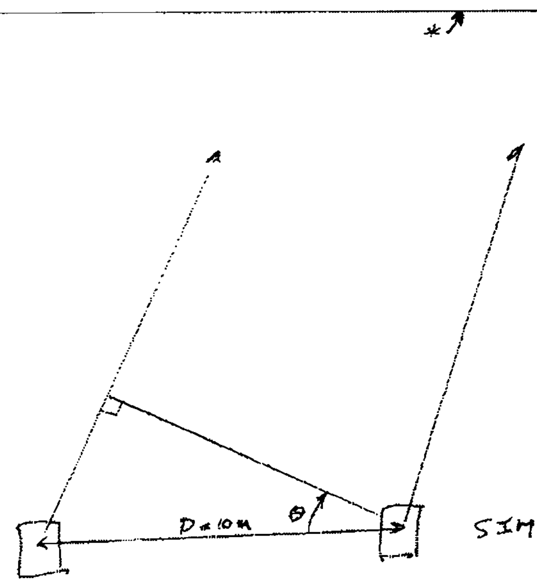
Nagaoka University
Presentation 1

JPL LOCKHEED MARTIN TRW

SIM Space Interferometry Mission

JPL



To get 5 picoradian accuracy
with baseline D = 10 meter
we need Metrology to know D

Define $\begin{cases} \text{Error in } \theta, & \Delta\theta \\ \text{Error in } D, & \Delta D \end{cases}$

$$\Delta\theta = \frac{\Delta D}{D} \longrightarrow \Delta D = D\Delta\theta = (10\,m)(5\times10^{-12})$$
$$= 50 \text{ picometers}$$

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Nagaoka University
Presentation 2

JPL LOCKHEED MARTIN TRW

SIM project description

- Launch in 2008:
- Pico-radian accuracy space "theodolite".
- Compares rapidly changing **angular positions** of local stars to unchanging distant "reference" objects (such as active galactic nuclei).
- Parallax angles as SIM orbits the sun provides accurate distance measurements to stars and nearest galaxies.
- Detects planets orbiting stars, providing planet mass and orbital parameters.
- Detects mysterious Massive Compact Halo Objects (MACHOs) which are a possible explanation for intergalactic dark matter, providing distance & mass from gravitational lensing measurements.
- Measures transverse velocities of stars locally and in nearest galaxies.
- Complements line-of-sight (Doppler) velocity measurements.

SIM Space Interferometry Mission

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Artist conception

SIM Space Interferometry Mission

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SIM specs

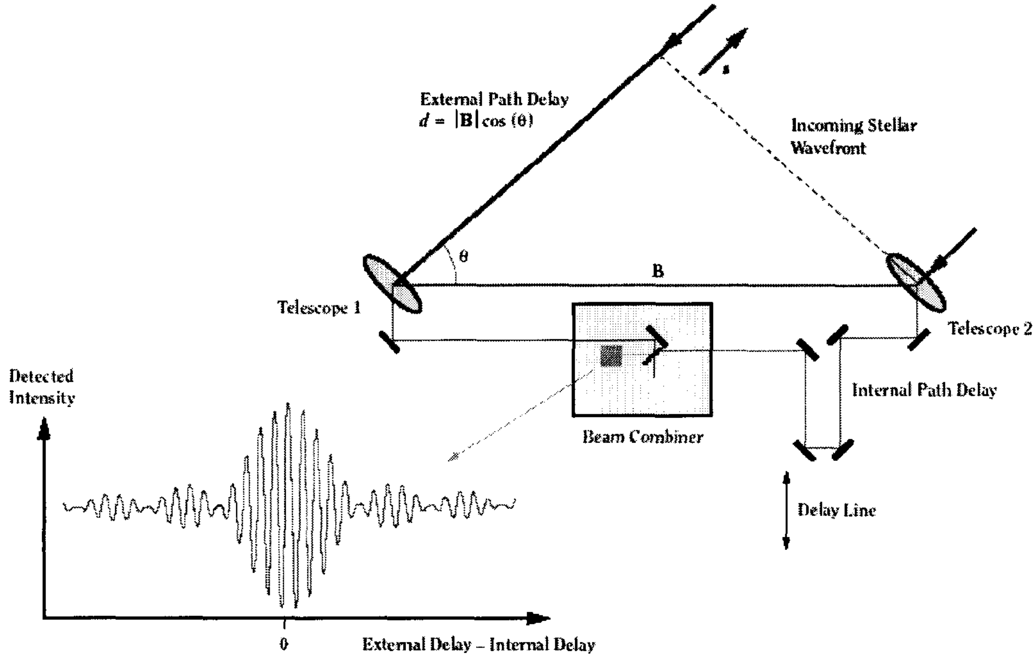
SIM Space Interferometry Mission

- Four stellar interferometers (two are for bright local "guide" stars, two for dimmer "science" objects.)
- ~10 meter baselines
- Angular accuracy: 5 pico-radians
- Interferometers measure starlight wavefronts to 50 picometer accuracy (because 5 pico-radians = 50 pm / 10 m).
- This implies that relative locations of interferometer optics must be known to better 50 picometers.

- Metrology in SIM is expected to measure distance between optics to ~10 pm **relative** accuracy.
- Metrology expected to measure same distance to ~10 micron absolute accuracy.

Michelson Interferometer

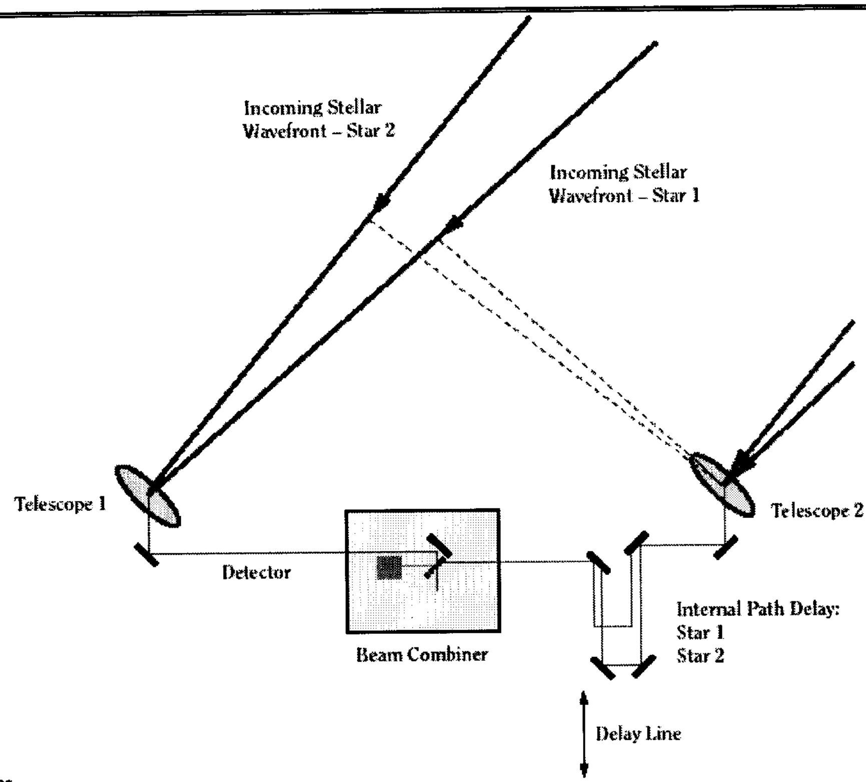
SIM Space Interferometry Mission



Michelson relative astrometry

SIM Space Interferometry Mission

If baseline length and orientation are known, the astrometric observ- able ($\mathbf{s}_1$–$\mathbf{s}_2$) can be deduced directly from the relative delay difference between the stars.

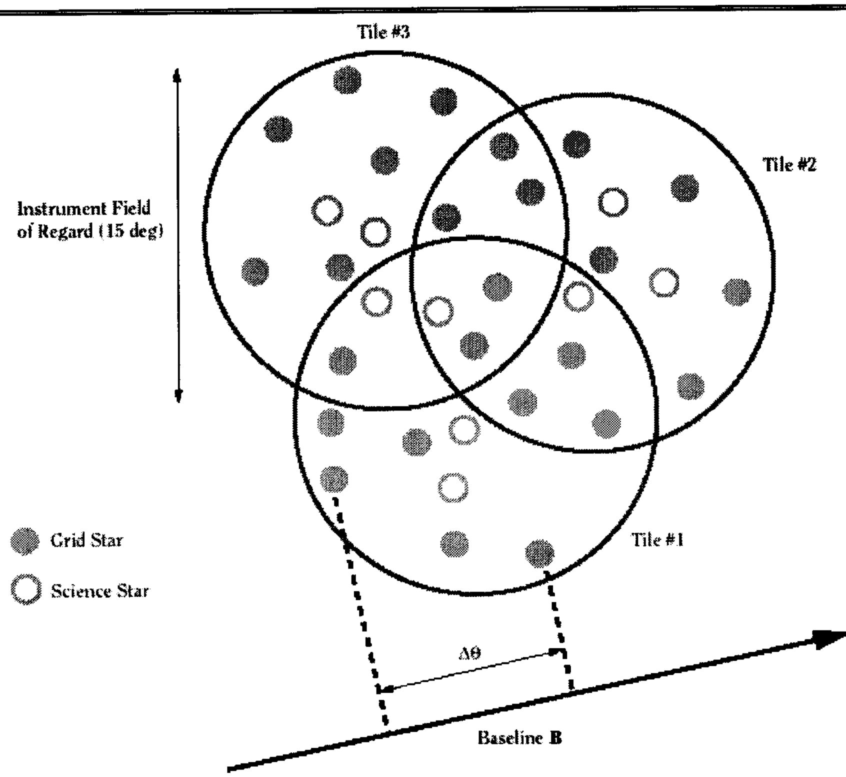


Global Astrometry

SIM Space Interferometry Mission

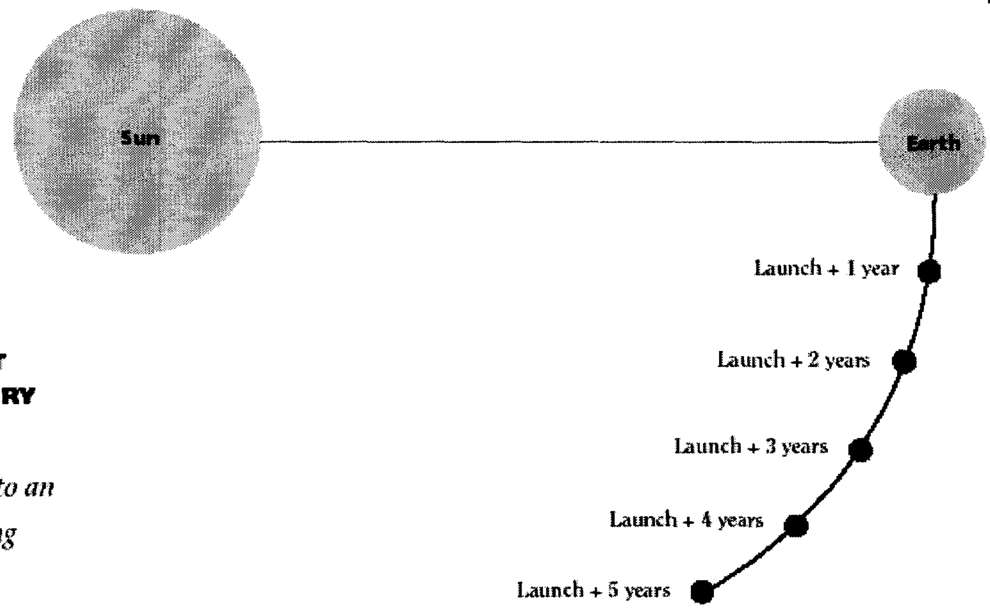
GLOBAL ASTROMETRY

SIM's astrometric "tiles." Grid stars tie the tile data into the global astrometric frame.



SIM orbit

SIM Space Interferometry Mission



SIM ORBIT TRAJECTORY

SIM will be launched into an Earth-trailing solar orbit.

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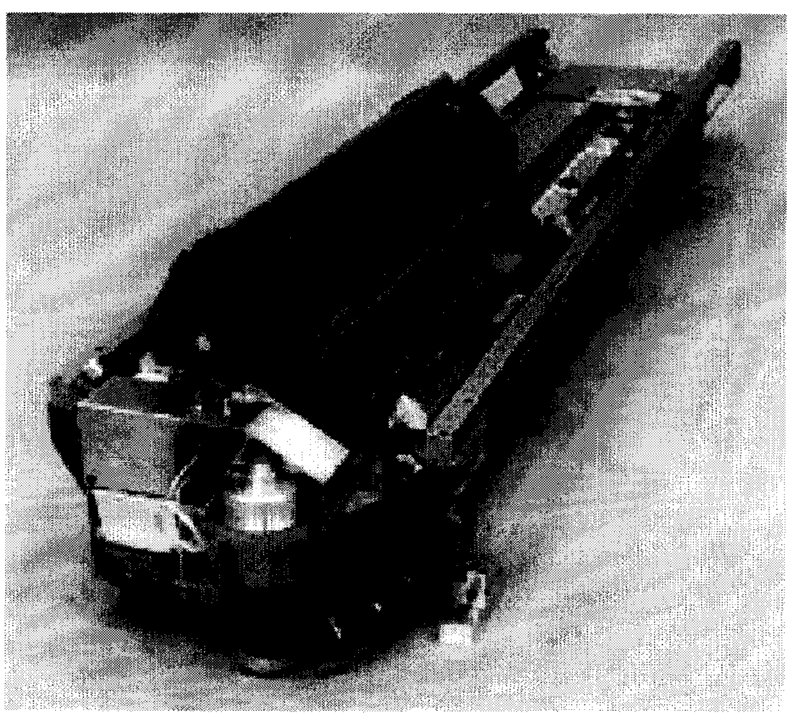
Optical delay line

SIM Space Interferometry Mission



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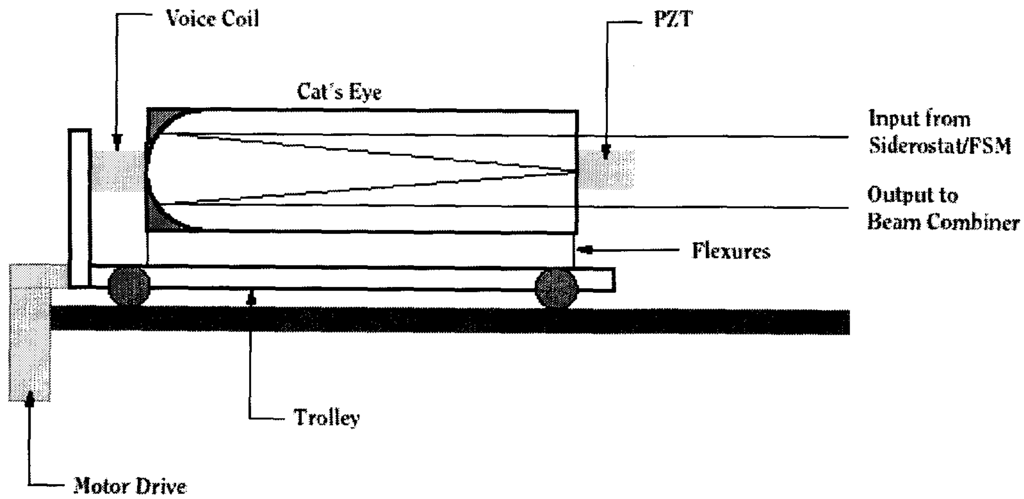
Optical delay line



SIM Space Interferometry Mission

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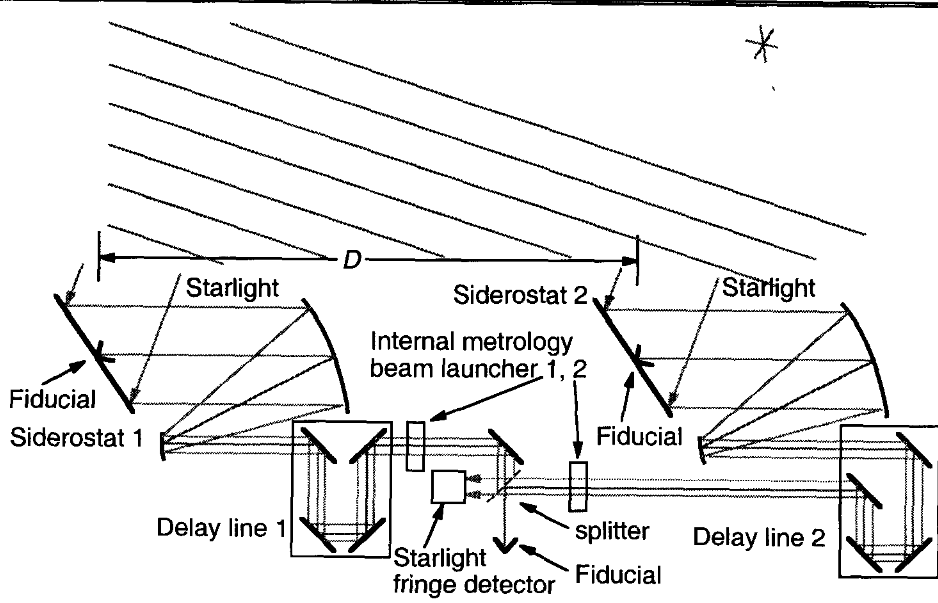
The role of metrology in SIM: internal metrology



Simplified sketch of SIM's internal metrology light path (red line) and starlight (blue). Internal metrology measures the difference in starlight path (adjusted by the delay lines) required to keep the central startlight fringe locked at the fringe detector. The baseline vector ***D*** is the vector from the center of siderostat 1 to siderostat 2.

SIM Space Interferometry Mission

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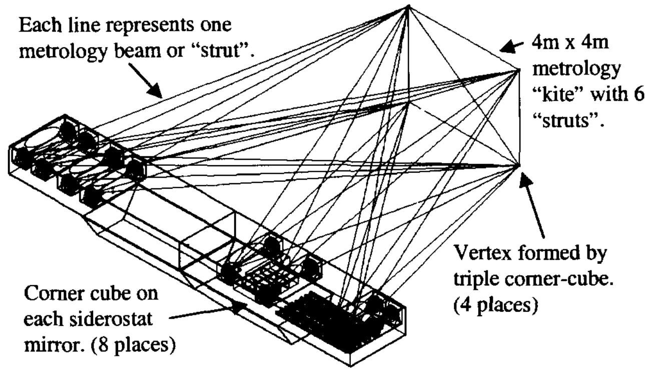
The role of metrology in SIM: External metrology

SIM Space Interferometry Mission



External metrology used to monitor the geometry of SIM to ~100 pm. *Geometry* means the precise lengths, relative directions and positions of D_1, D_2, D_3, the baseline vectors of the three interferometers (science and two reference).

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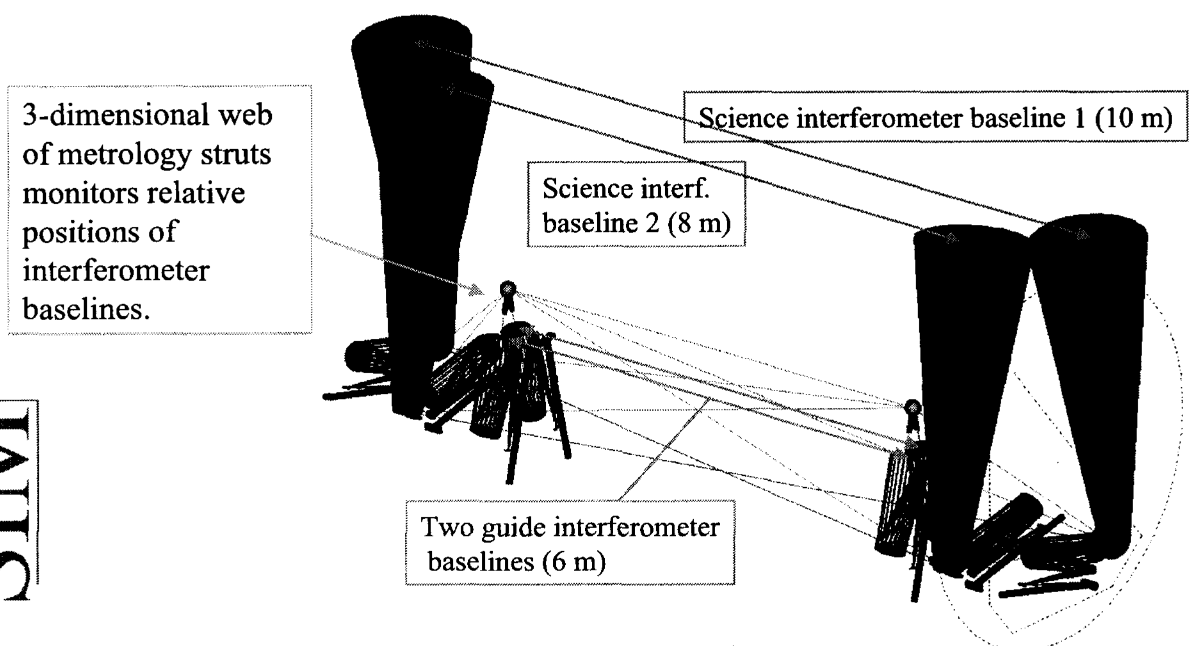
Metrology structure ties the interferometers together

SIM Space Interferometry Mission



Internal metrology (not shown) measures starlight propagation distance to beam combiners.

A NASA Origins Mission

NASA

SIM metrology requirements

JPL

SIM Space Interferometry Mission

	Internal metrology requirement	External metrology requirement
Number of gauges	8	42 (kite: 6, roll estimation: 4, siderostats: 32)
Number of gauges for mission success (assuming dispersed failures)	6 (two siderostats are spares)	24 (Kite: 5, roll estimation: 1, siderostat fiducials: 24)
Distance between fiducials	20 meters	Varies: shortest are 4 meters, longest are 12 meters.
Motion; ranges of distances	2.6 meters while changing stars; 10 microns while observing	10 microns
Velocity	2 cm/s while changing stars, 1 micron/sec while observing	<10 microns/sec ?
Accuracy (absolute)	Solved for with astrometric data	3 microns rms
Accuracy (relative)	15 pm rms (1 hour time scale); 8 pm rms (5 minute s)	
Temperature coefficient	2 pm/mK (soak); 50 pm/mK (sensitivity to gradients)	

SIM metrology requirements, subject to change as SIM's design evolves.

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NASA

Current metrology performance

JPL

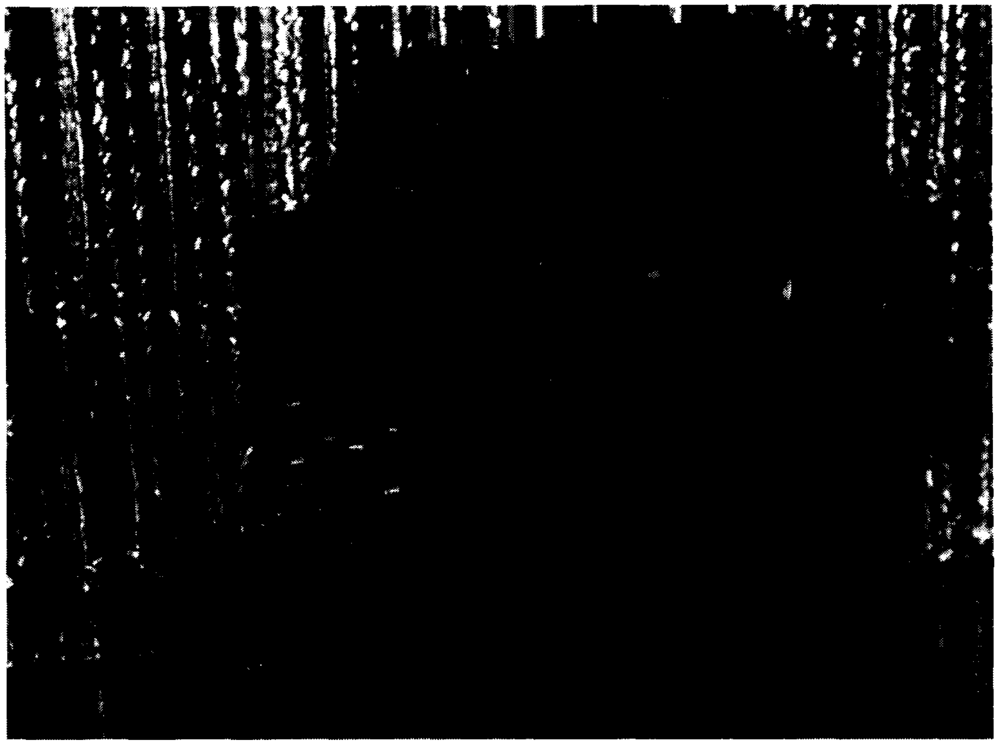
SIM Space Interferometry Mission

Wavelength	1.3 microns
Distance between fiducials	2.5 meters
Beam diameter	5 mm
Accuracy (absolute)	~5 microns
Accuracy (relative)	~30 picometers
Temperature coefficient	~8 nm/K

A NASA Origins Mission

JPL LOCKHEED MARTIN TRW

Proof-of-concept metrology fiducial mounted on siderostat



SIM Space Interferometry Mission

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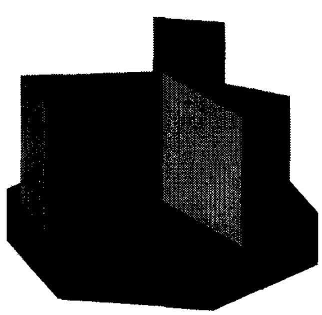
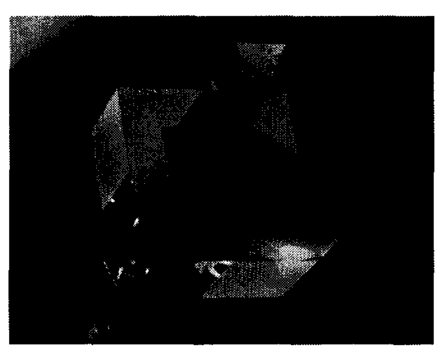
Metrology Fiducials



SIM Triple Corner Cube



Prototype TCC

SIM Space Interferometry Mission

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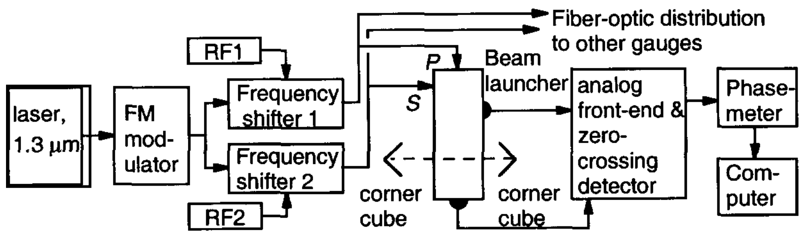
Metrology system block diagram



SIM Space Interferometry Mission

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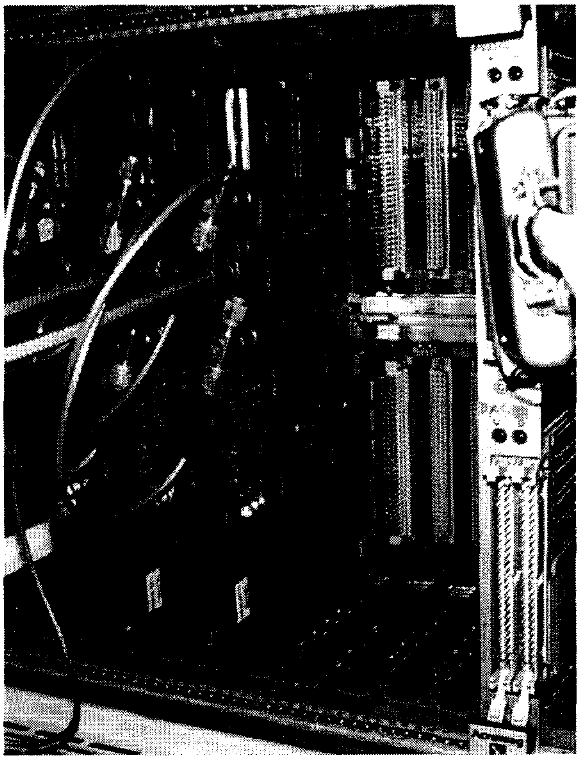
Digital phasemeter

- VME based
- 6 gauges per board
- (This setup can handle 18 gauges)



SIM Space Interferometry Mission

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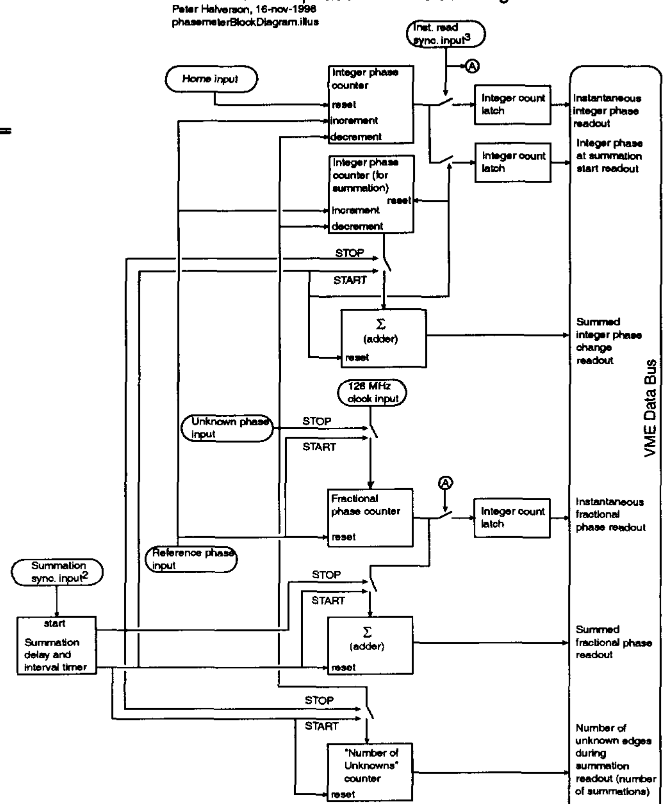
Digital phasemeter perfomance

Number of channels (gauges)	6
Maximum clock frequency	128 MHz
Stability	10^{-5} cycles (6.5 pm) for ambient temperature held to 0.1 C
Range	$2^{32}=4.3\times10^{9}$ cycles. (2795 meters)
Heterodyne frequency range	1954 Hz to 1.33 MHz
Phase resolution (no averaging)	1.6×10^{-5} cycles (10 pm) at 2 kHz to 0.01 cycles (650 pm) at 1.3 MHz heterodyne frequency. (Improves with averaging)
Velocity range at maximum heterodyne frequency	+/- 0.88×10^{6} cycles per second (0.58 meters/second)
Temperature sensitivity	<500 picoseconds/C (32 pm/C)

Specifications for the JPL phasemeter. Specifications in picometers assume a 100 kHz heterodyne frequency and 1.3 micron wavelength.

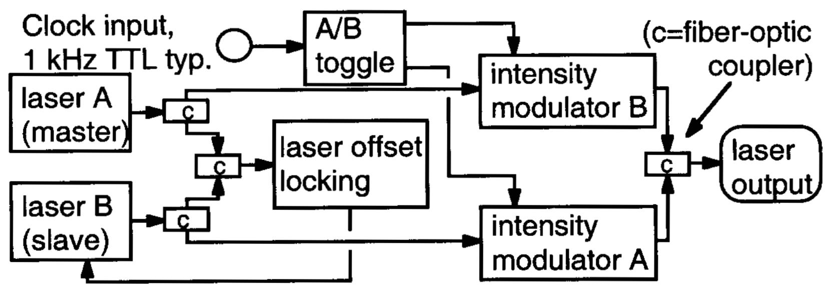
The JPL/MAM phasemeter - block diagram.

Peter Halverson, 16-nov-1998
phasemeterBlockDiagram.illus



NOTES:
0) This diagram is highly simplified, for learning purposes only.
1) The phasemeter board has 6 channels. Only one is shown in this diagram.
2) The "summation sync input" is called the "slow clock" in the phasemeter schematics.
3) The "instantaneous read sync. input" is called the "read clock" in the phasemeter schematics.
4) The instantaneous phase may be latched in three ways: (a) upon each instantaneous read sync. input edge (b) upon software *FREEZE and (c) upon each Unknown phase input edge. Methods (b)* and (c) have been omitted for clarity.
5) The integer phase may be reset in three ways: (a) upon HOME input edge, (b) upon "global clear int" command and (c) upon "clear integer counter" command. Methods (b) and (c) have been omitted for clarity.

Upgrade for absolute metrology

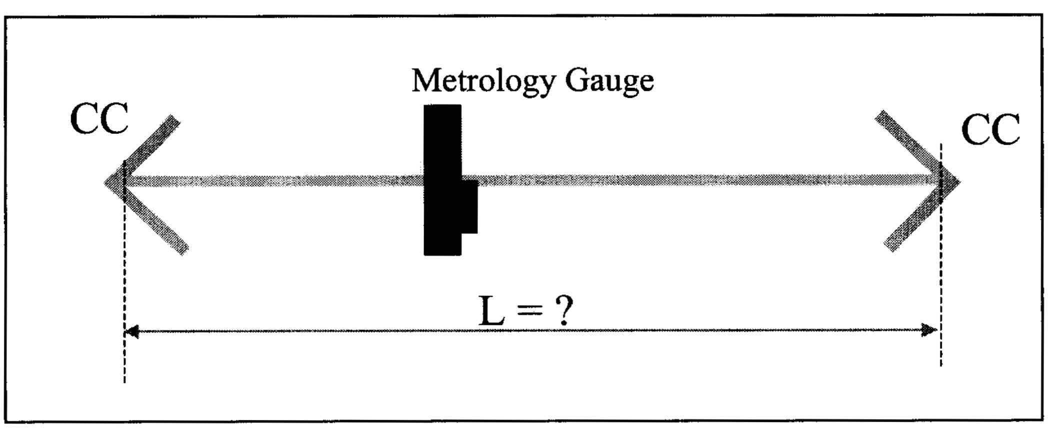


Laser source upgrade for absolute metrology. Light from lasers A and B are held 15 GHz apart by the laser offset locking electronics. A clock signal (in practice, the phasemeter readout clock) toggles intensity modulators A and B. The resulting 500 Hz rate, 15 GHz amplitude FM is fed to the metrology gauge for absolute calibration, as described in the text.

- Synthetic wavelength is 20 cm.
- Know absolute distance modulo 10 cm
- Current accuracy: ~5 microns

Absolute Metrology

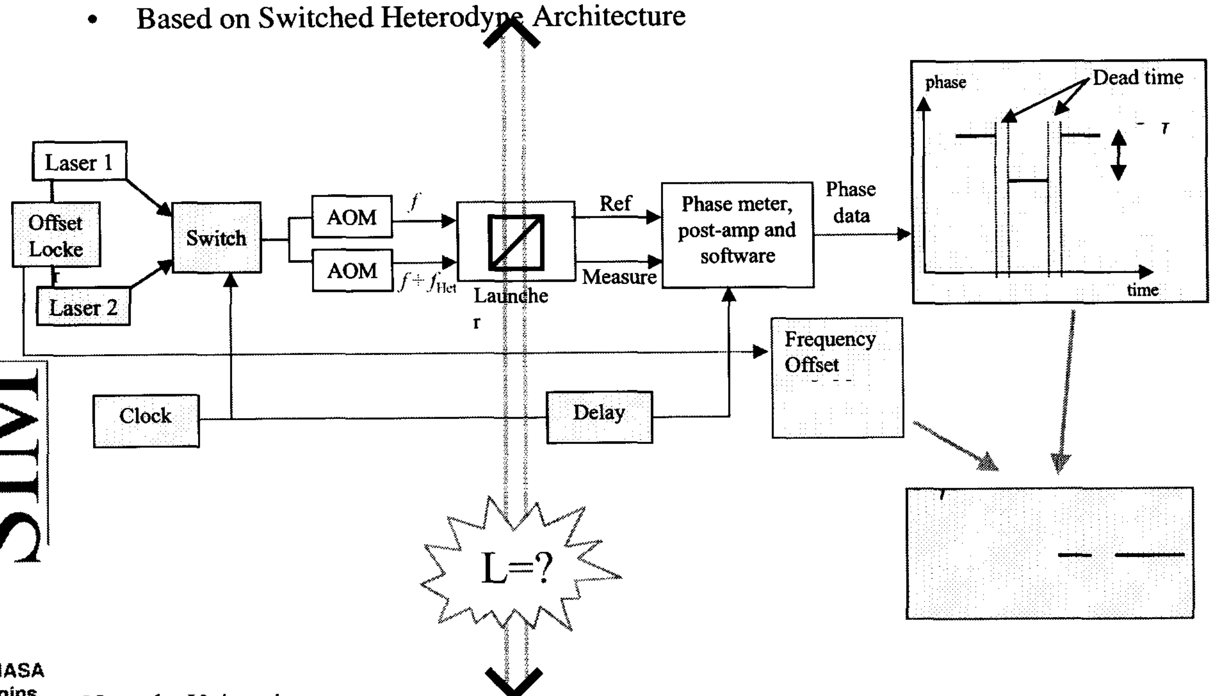
- SIM external metrology requires knowledge of absolute distances to 3 μm
- For Kite, the requirement is 10 μm



Absolute Metrology Gauge Implementation

SIM Space Interferometry Mission

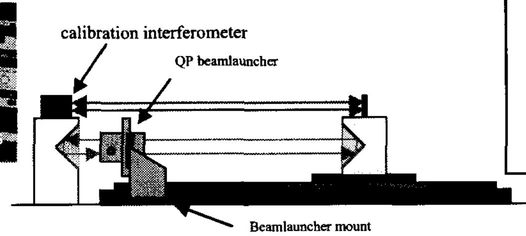
- Based on Switched Heterodyne Architecture

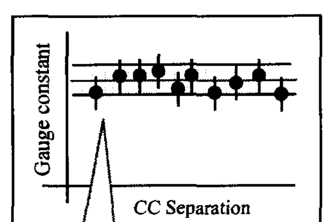


Absolute Metrology Gauge Offset Calibration

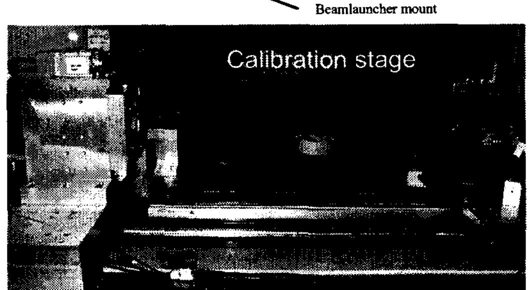
SIM Space Interferometry Mission

- Basic approach:
  1. bring two fiducials into repeatable, measurable separation via contact
  2. measure the change in the distance as they are separated
  3. insert Abs Met gauge: "Gauge constant" = Abs Met – Calibration
  4. repeat for a range of fiducial separations

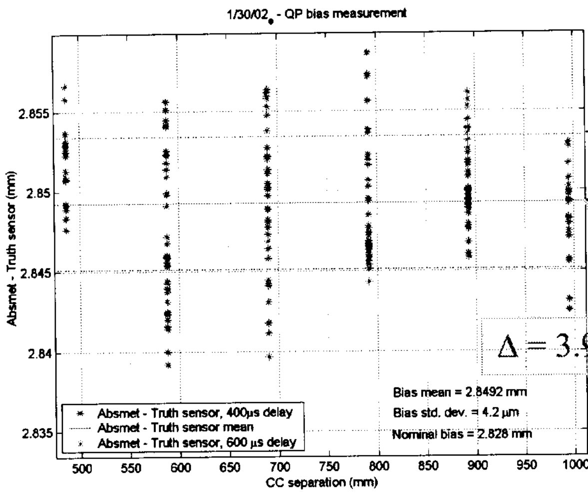




Vertical spread measures absolute metrology system performance



Absolute Metrology Performance Data

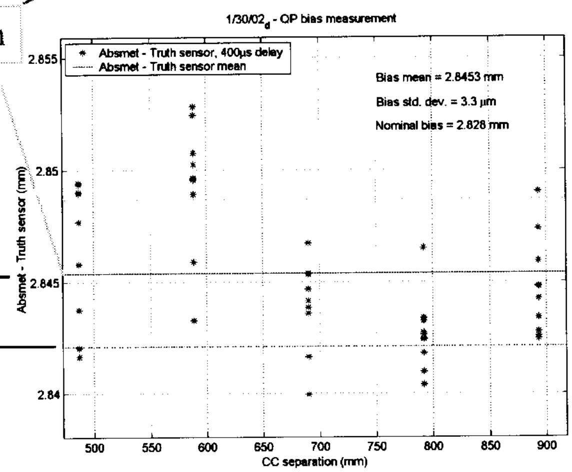


Two separate runs used to get performance estimate:

σ = 4.2 μm

$\varepsilon_{Abs\ Met} < 6$ μm

Δ = 3.9 μm



σ = 3.3 μm

SI

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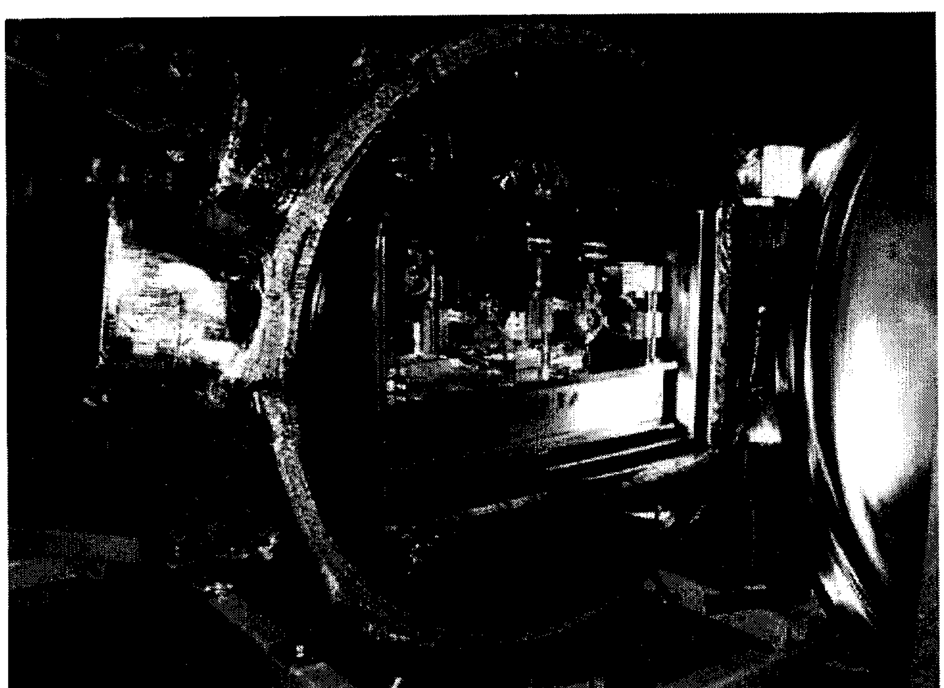
JPL LOCKHEED

Test facility for metrology gauges

SIM Space Interferometry Mission



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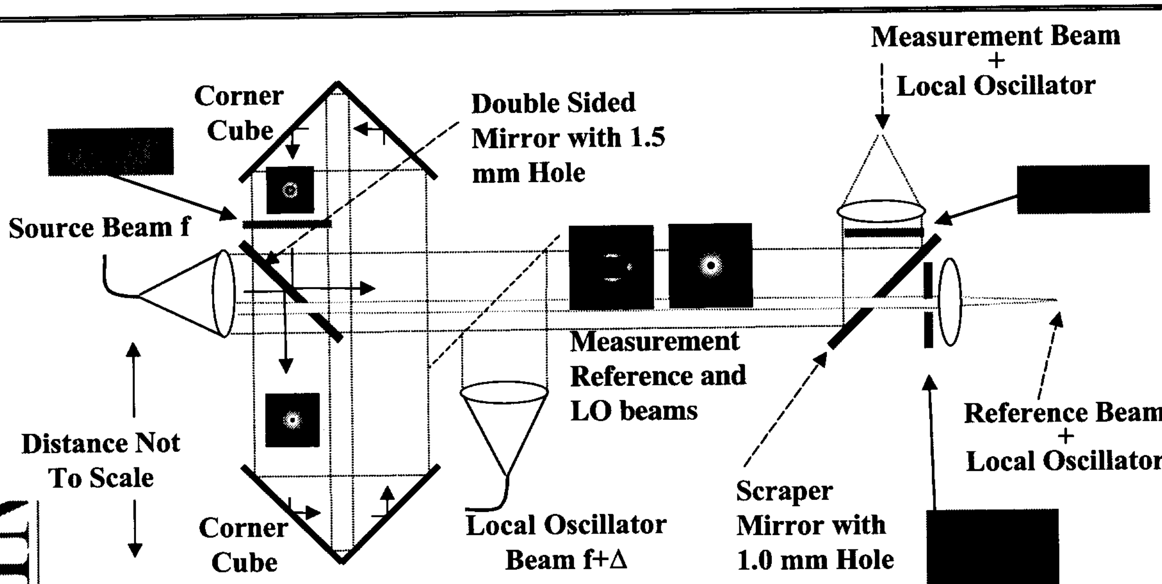
JPL LOCKHEED MARTIN TRW

QP Design Concept

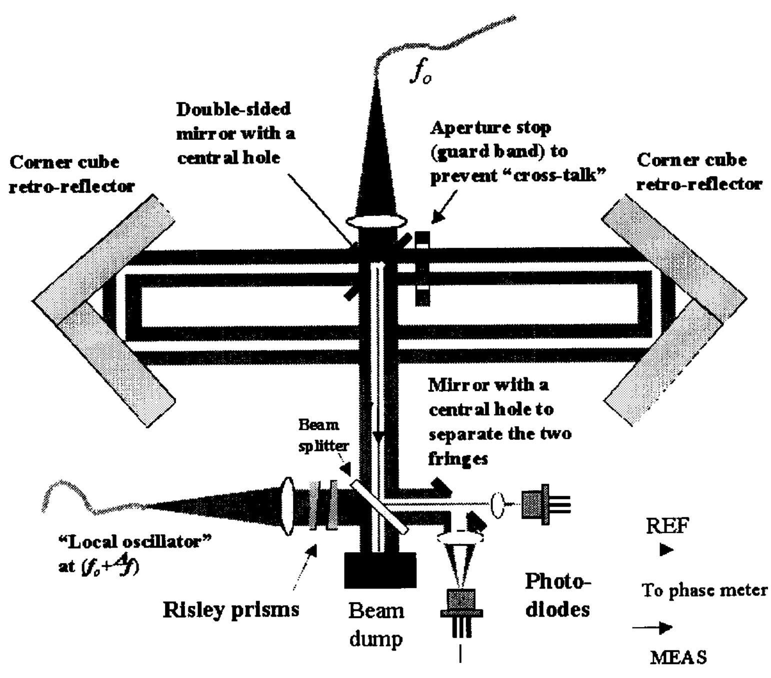
SIM Space Interferometry Mission



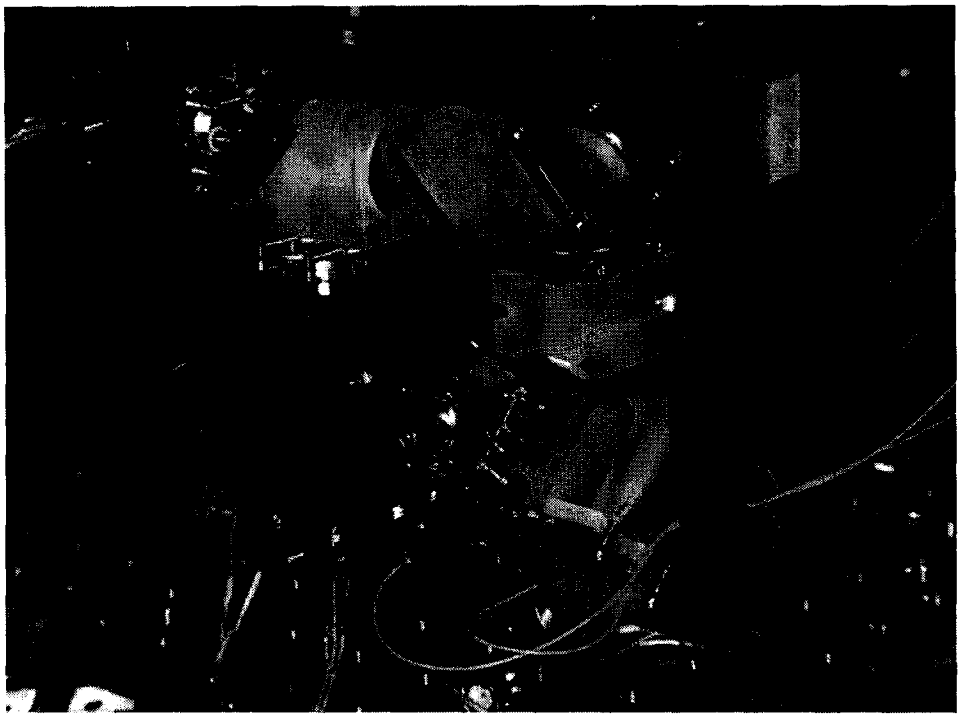
- Source beam is physically split at double sided mirror into a small narrow reference beam which passes directly to the detector and the larger measurement beam that is circulated around the racetrack.
- The reference and measurement beams are rejoined but remain physically separated on the other side of the double sided mirror. They each mix with the LO at the beam splitter.
- The measurement and reference beams are then redirected to their own detector by the scraper mirror each with their own share of the LO beam.

Metrology head concept

SIM Space Interferometry Mission



Metrology gauge setup for thermal test



SIM Space Interferometry Mission

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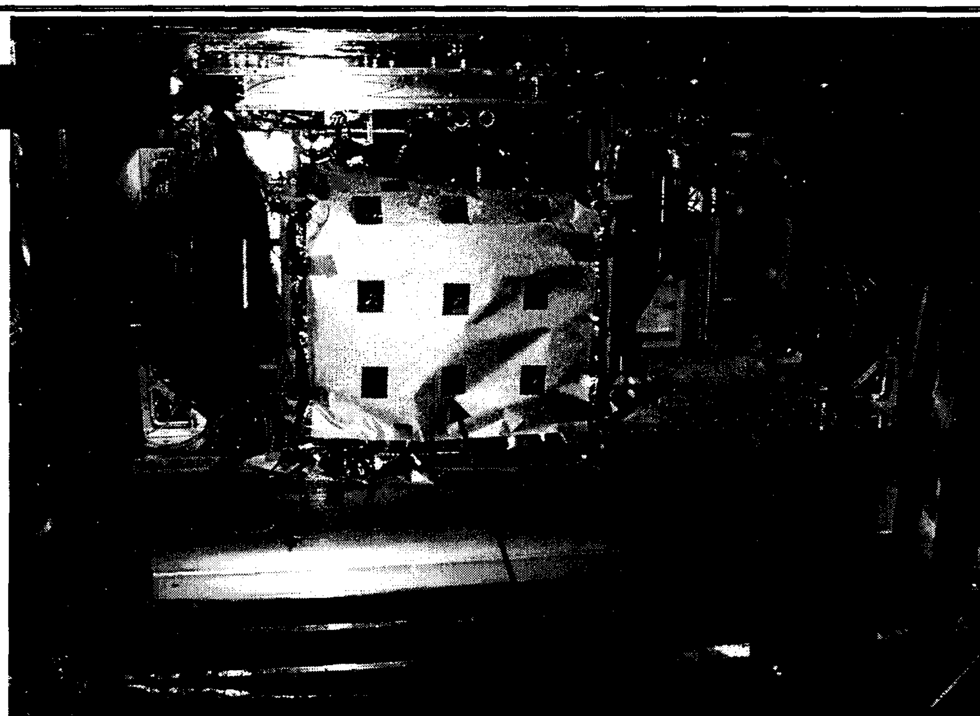
Nagaoka University

2-Gauge Test Configuration



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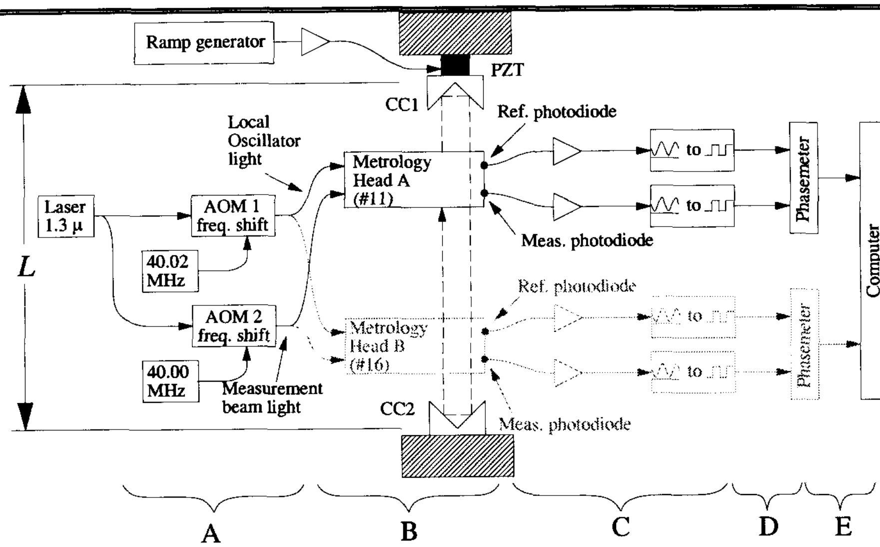
Nagaoka University

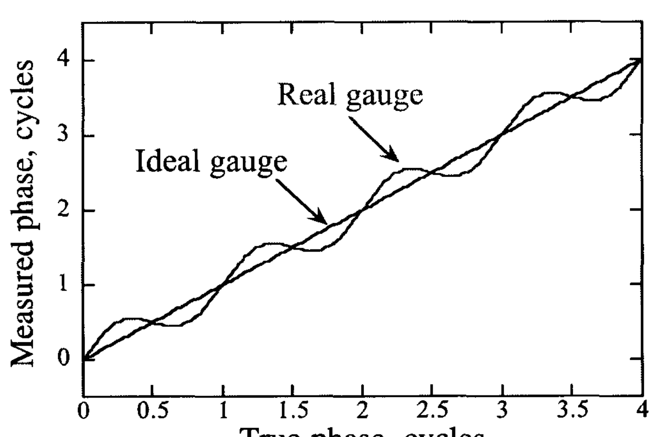
Metrology gauge test facility block diagram



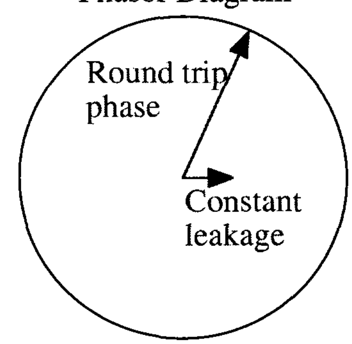
Block diagram of laser heterodyne interferometer which measures changes in *L*, the distance between retroreflectors CC1 and CC2. An optional second gauge (shown in gray) can measure the same distance, allowing useful gauge comparisons. The letters A..E indicate regions where cyclic error originates. For cyclic error detection, the piezoelectric (PZT) actuator moves CC1 with a voltage ramp that has been precompensated for piezo hysteresis, to achieve near-constant velocity.

Cyclic error: a periodic non-linearity

- Imperfect split of Measurement beam away from reference beam causes constant leakage of M light into wrong path.
- At recombination: M beam + leakage M causes periodic phase advance/retardation ----> **Cyclic Error**
- To keep cyclic error below 10 pm, must have
  - Optical leakage < 80 dB (low optical cross-talk)
  - Electronic cross-talk < 80 dB
  - Or, if we're lucky, use some "tricks".



Phasor Diagram

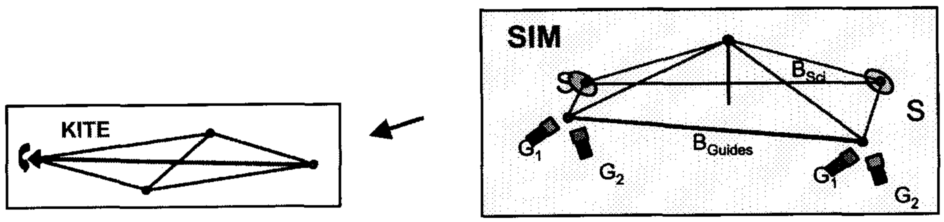


(2π of phase for every λ of OPD change)

The Role of Kite

SIM Space Interferometry Mission

- The role of Kite is to verify SIM external metrology performance
- SIM external metrology tracks baseline changes as the fiducials move
- Testing up to now has been 1D (2-gauge)
- The Kite 2D truss will show it can track similar changes to the level required by the SIM performance model (Currently PM36a).

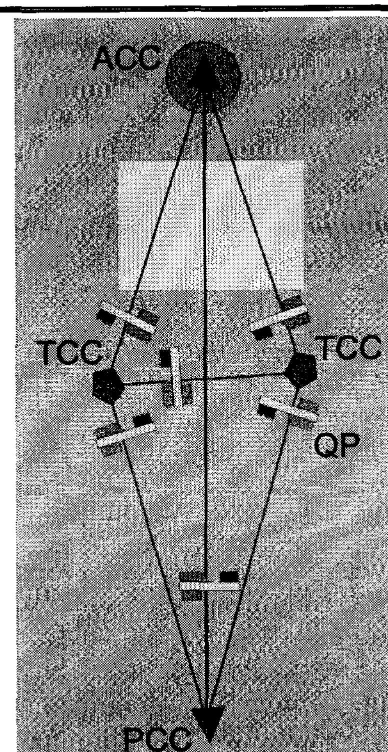


- Ideally, Kite performance should be limited by the gauge performance, where the gauge performance is derived from the SIM error budget.

Kite Approach and Architecture

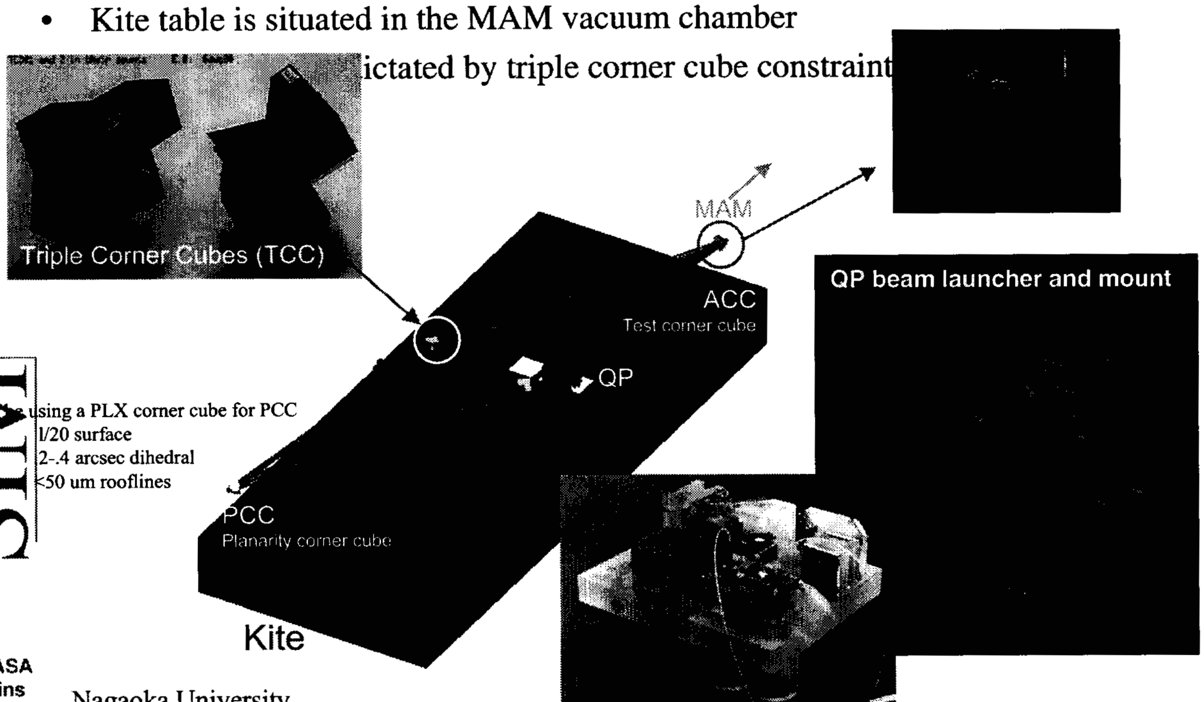
SIM Space Interferometry Mission

- Build a **redundant** metrology truss:
  - 4 fiducials (2 corner cubes + 2 triple corner cubes)
  - 6 metrology gauges connecting the 4 vertices
  - All in a plane (to required level)
- Compare the readings from one gauge with prediction using the other 5 as a CC is articulated by various amounts of tip and tilt or translation
- Account for CC imperfections using CC calibration and model
- Take the difference of the residual before vs after
- Show the rms error is below requirement for the various cases of:
  - 0.5 deg articulation (NA) at 50 pm rms
  - 7.5 deg articulation (WA) at 300 pm rms
  - simulated PSS thermal deformation (1um, 10 um)

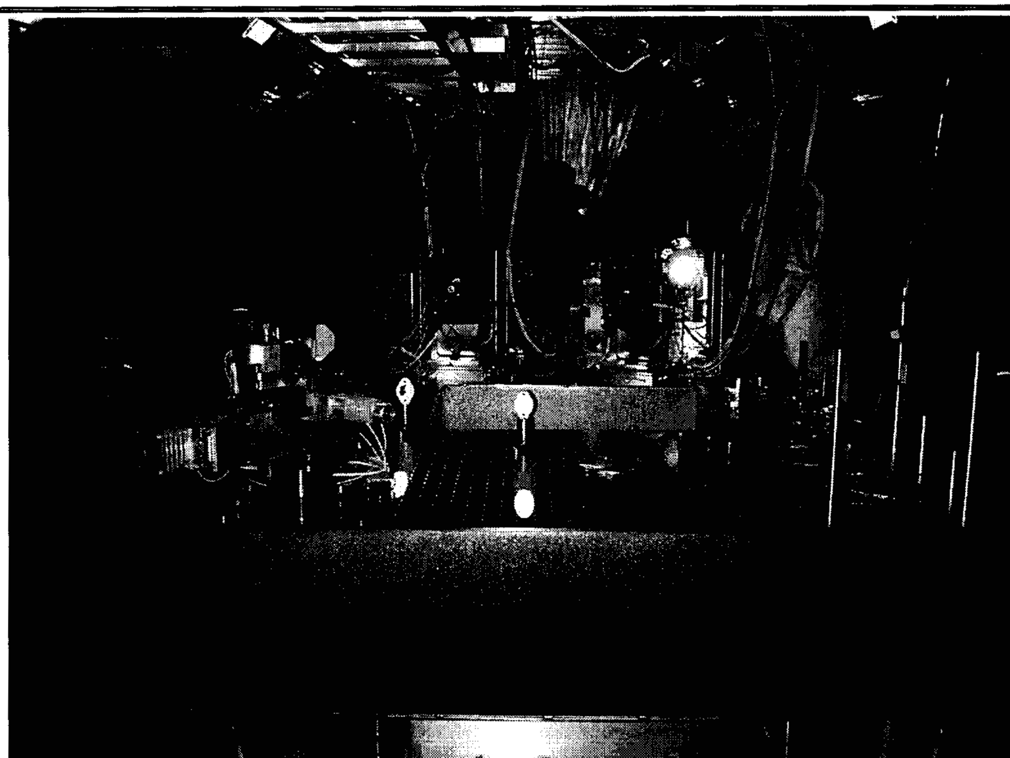


Kite Testbed Configuration

- Kite table is situated in the MAM vacuum chamber
- ...ictated by triple corner cube constraint



Kite Installed in Vacuum Chamber



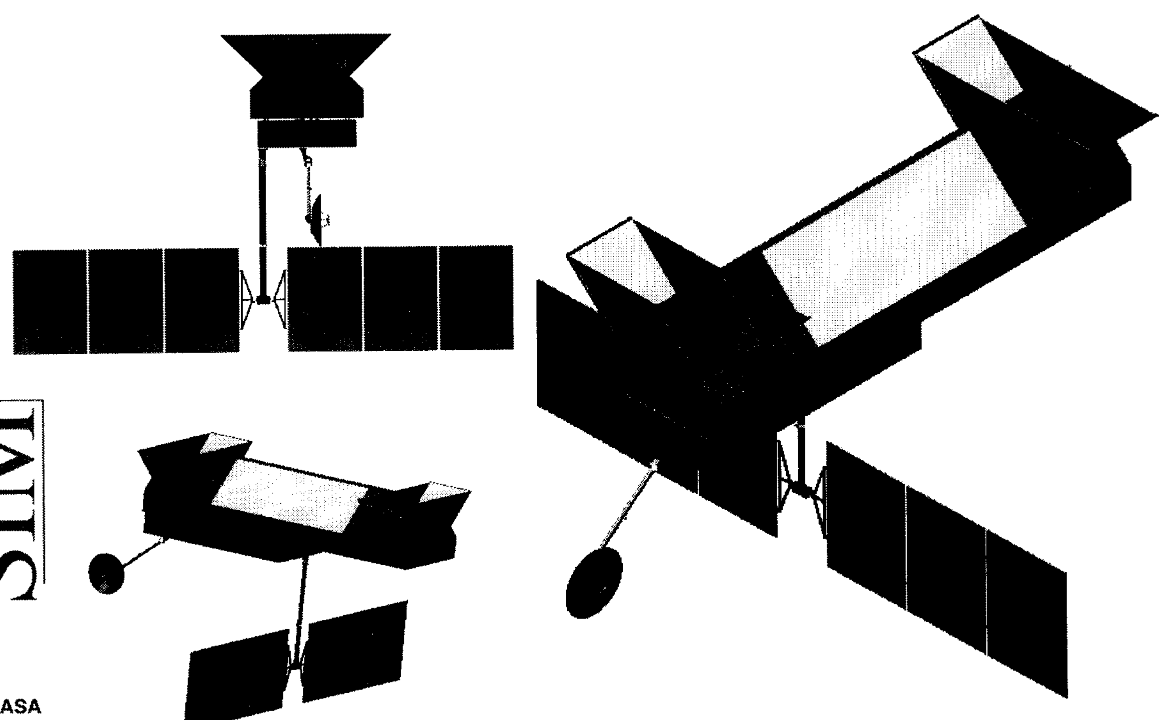
SIM evolves...

SIM Space Interferometry Mission

- New configuration uses fewer metrology measurements
- Is more compact: fits into Space Shuttle or Expendable Launch Vehicle

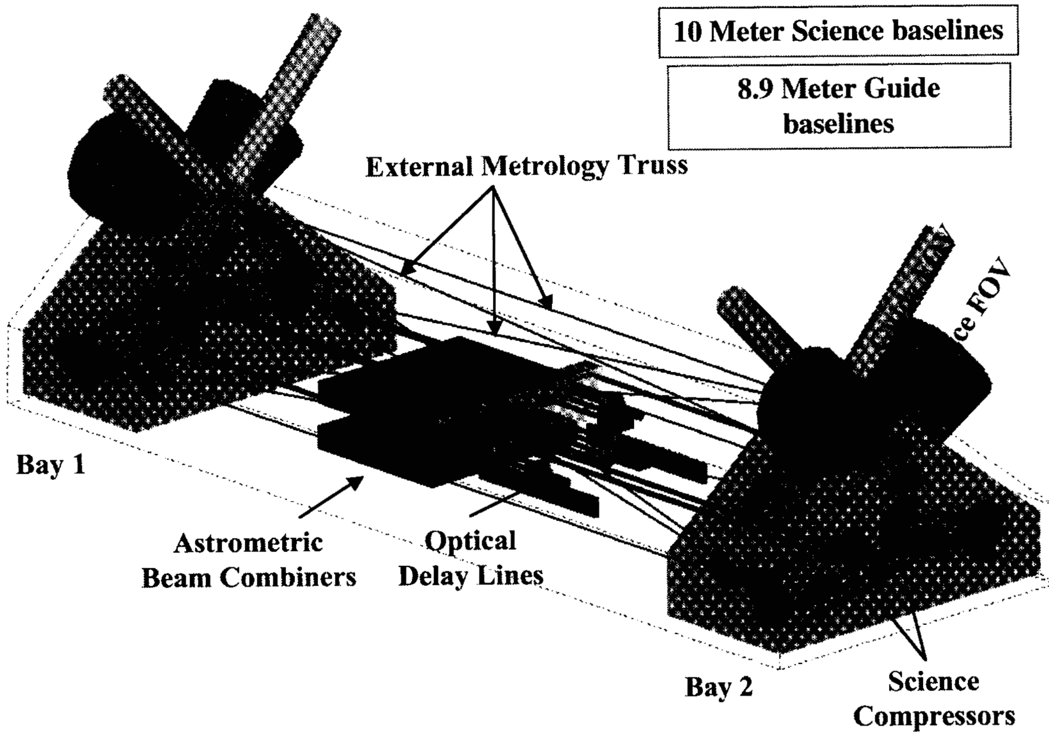
SIM (new version) Fully Deployed On Orbit

SIM Space Interferometry Mission



Shared Baseline Interferometer Configuration

SIM Space Interferometry Mission



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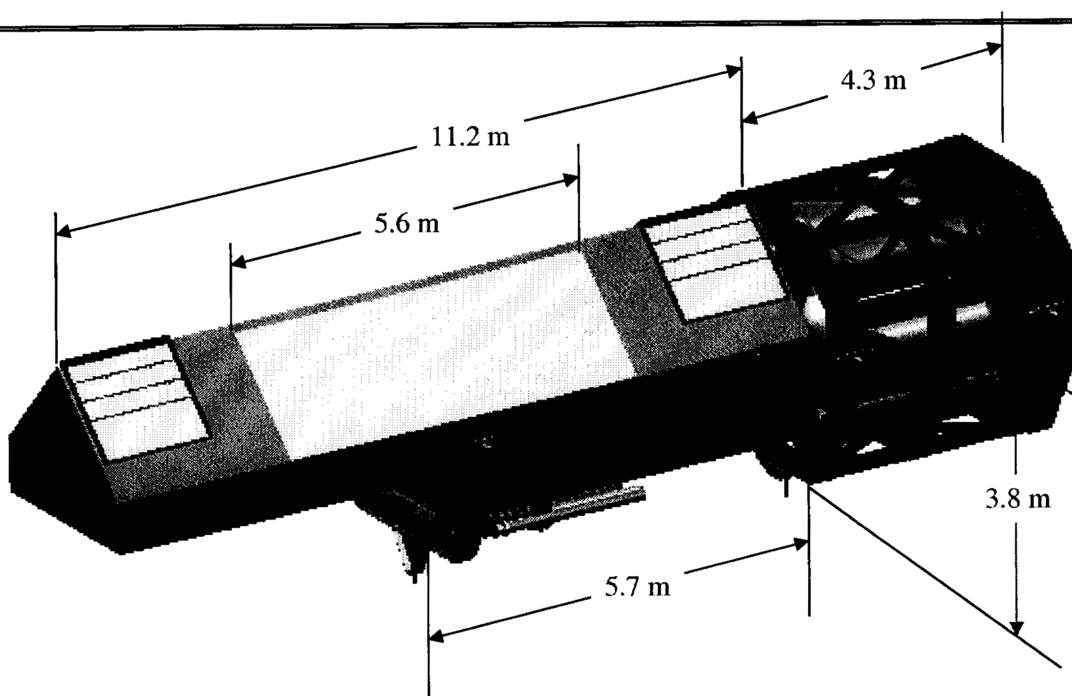
SIM and IPM Configuration

SIM Space Interferometry Mission



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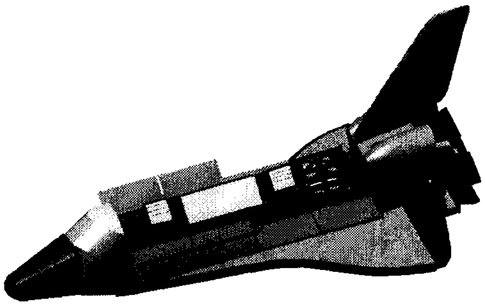
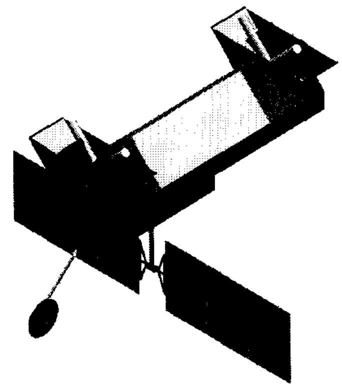
JPL LOCKHEED MARTIN TRW

Fit into shuttle bay or EELV



In Shuttle Bay

In EELV Delta IV
Heavy Fairing



Deployable 2-piece sunshade/contaminatio n cover